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RADIATION MONITORING WITH NUCLEAR EMULSIONS ON PROJECT
GEMINI. II. RESULTS ON THE 14-DAY MISSION GEMINI VII

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SUMMARY PAGE

THE PROBLEM

On the 14-day mission Gemini VII, radiation monitoring with small packs of nuclear emulsions within the astronauts' space suits was carried out in the same way as on missions GT-IV and V described earlier. It was a singular advantage of GT-VII that the background of the nucleonic component in the sea level controls, which the emulsions inevitably accumulate during the time between manufacture and development, was less than 4 per cent of the flight exposure. By track evaluation of the GT-VII emulsions, therefore, a unique opportunity arose to obtain statistically significant counts in small emulsion areas, thus allowing analysis of local variations of the low energy proton flux even within the same film sheet.

FINDINGS

A detailed track and grain count analysis carried out on the G.5/K.2 emulsion pair of Pack 4 (command pilot, thigh) furnished a total mission dose of 190 millirads from protons. The count of proton enders corrected for enders from disintegration stars in the same emulsion pair was found to be 32.2 per mm^2 emulsion area. The five other packs were subjected only to enders counts which were found to vary from 27 to 39.5 enders/ mm^2 . Assuming that the configuration of the energy spectrum is essentially the same in all packs, one would obtain a variation of the corresponding doses from 159 to 233 millirads.

The 200 micra K.2 emulsion in Pack 9 (pilot, thigh) was subjected to an enders count over its entire 1 by 1½-inch area. The count was found to vary from 29.9 in the lower left corner to 40.2 enders/ mm^2 in the upper right, with a complex distribution pattern showing at least one intermediate minimum in the center of the film sheet and one intermediate maximum in the middle of the lower edge.

The plot of cumulative dose versus LET shows that 40 per cent of the total dose is due to protons of less than 0.1 g/cm^2 range in tissue. The results confirm earlier findings indicating that, because of the large percentage of soft radiation, the local dose within the capsule sensitively depends on the local shielding geometry.

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INTRODUCTION

On 4 December 1965 the mission Gemini VII was launched into an elliptical orbit of 28.9° -inclination with a perigee of 100 and an apogee of 204 miles. The vehicle re-entered the atmosphere on 18 December after completing 220 orbits in 330.6 hours. From the standpoint of radiation monitoring with nuclear emulsions, this mission is of particular interest inasmuch as its long duration of fourteen days provided, for the first time on a manned mission, an exposure of such magnitude that the background, which emulsion pellicles inevitably accumulate in the time span between manufacture and processing, was insignificant. To be sure, a maximum dose of 233 millirads from trapped protons as recorded on the body surface on Gemini VII is not of significance from the radiation safety viewpoint. However, recordings of this exposure with nuclear emulsions are of considerable interest since they furnish information on the linear energy transfer (LET) spectrum of the proton flux, thereby allowing inferences on the energy spectrum and the depth of penetration in tissue. The following report presents this information as it follows from the track and grain count evaluation of Ilford G.5/K.2 emulsion pairs flown on the mission. In addition to nuclear emulsion sheets, the radiation packs also contained thermoluminescent radiation sensors. Dose measurements with these sensors have been reported earlier by Richmond, Davis, and Lill (1). As these readings agree well with the emulsion findings, main emphasis in the present account is placed on the LET spectrum and the directional properties of the flux as these characteristics cannot be determined with thermoluminescent dosimeters.

EXPERIMENTAL DESIGN AND EVALUATION PROCEDURE

In an earlier report (2), hereafter referred to as Report 33, the rationale for the experimental design and the evaluation technique for missions Gemini IV and V have been described. Though all these details remain unchanged for Gemini VII, it might be pointed out once again that the nature of the radiation exposure in the South Atlantic Anomaly is uniquely suited for measurements with very small emulsion volumes because the bulk of the incident flux is made up of low energy protons. For galactic exposure, conditions are basically different because practically all low energy protons are secondaries from nuclear interactions of high energy primaries in the local material surrounding the emulsion and in the emulsion pellicles themselves. Identification of the true primaries in track populations from galactic exposure, therefore, is an involved procedure requiring large emulsion volumes and the use of scan lines for separate evaluation of the peripheral sections of the emulsion volume. For Gemini type missions all these provisions can be dispensed with because more than 90 per cent of the astronauts' radiation exposure is due to trapped protons in the Anomaly, i.e., due to a proton flux heavily centering on low and very low energies. While this creates the complication of an almost infinitely complex radiation field inside the vehicle and the astronauts' bodies because of the low penetrating power of the bulk of the flux, it has at least the one advantage that flux and energy spectrum at any given location can be determined with a very small emulsion volume.

Contrary to earlier Gemini missions, on which each astronaut carried four radiation packs (helmet, left chest, right chest, thigh pocket), the pack in the helmet was omitted on Gemini VII because the astronauts took off their helmets for longer time periods. In all other instances procedures were identical to those on missions Gemini IV and V.

As pointed out in Report 33, the local energy spectrum of the proton flux in the vehicle is a wide continuum extending from zero Mev to very high energies where the flux eventually drops below the level of galactic protons. However, as pointed out before, the bulk of the flux producing more than 90 per cent of the total dose is concentrated in the energy interval from zero to a few hundred Mev. Though it is customary to characterize heterogeneous proton beams by their energy spectra, it should be realized that the grain count evaluation of a population of tracks in nuclear emulsion actually furnishes the LET spectrum because it is the LET of a particle that determines the grain count. Since LET and track length per unit volume, at the same time, determine the energy dissipation per unit volume, i.e., the absorbed dose, it is seen that the evaluation of dose as such does not require recourse to the energy spectrum. In presenting emulsion data the latter spectrum can only be established indirectly by applying the LET/energy function for emulsion to the LET spectrum obtained from the grain count.

Dealing directly with the LET spectrum instead of the energy spectrum has the additional advantage that it allows immediate reference to the grain count/LET function for determining the relative accuracies with which a certain LET interval is monitored by different types of emulsions. In the present analysis this is of special importance because sustained resolution over the wide energy band from zero to several hundred Mev required the combined use of two types of emulsions, Ilford G.5 and K.2, which offer maximum resolution in two different LET regions. For better demonstration of these relationships it seemed preferable to present the results in terms of LET rather than of kinetic energy, especially since the characteristics of the energy spectrum have been thoroughly analyzed in Report 33.

The objection could be raised that the dose contribution from minimum ionization tracks cannot be determined correctly since an unknown number of such tracks might be missed in the scan because of their low grain count which makes it difficult to recognize them in the comparatively high background of single grains in the G.5 emulsions. However, if all single grains in a visual field are counted and aligned to fictitious tracks, once in a sea level control and once in a flown emulsion, it is found that the dose contribution is insignificant. Hence a laborious search for such tracks in the G.5 emulsions does not pay off in any significant increase of accuracy. Scan, re-scan tests in flown G.5 emulsions indicated that the counting efficiency starts dropping below 100 per cent at about 30 grains/100 micra E. In K.2 emulsion, because of the much smaller background, tracks of 10 grains/micra E are still easily recognized. The scan limit, therefore, was set at that grain density though the classes in the region from 10 to 40 grains/100 micra E actually are not used in the determination of dose, as will be seen in the next section.

LET SPECTRUM AND TISSUE DOSE

In view of the fact that accumulation of statistically significant data on grain count distributions for track populations in emulsions is a time-consuming task, scanning efforts were concentrated on one G.5 and K.2 emulsion pair rather than dissipated on sampling the entire material from six different radiation packs. This limitation seemed all the more acceptable because the thermoluminescent sensors mentioned before had already furnished information on the total absorbed doses at the six positions within the astronauts' space suits. As an arbitrary selection, the G.5/K.2 pair from the pack in the command pilot's thigh pocket was singled out for grain count analysis whereas the five other packs were evaluated merely by enders counts which are discussed in a later section.

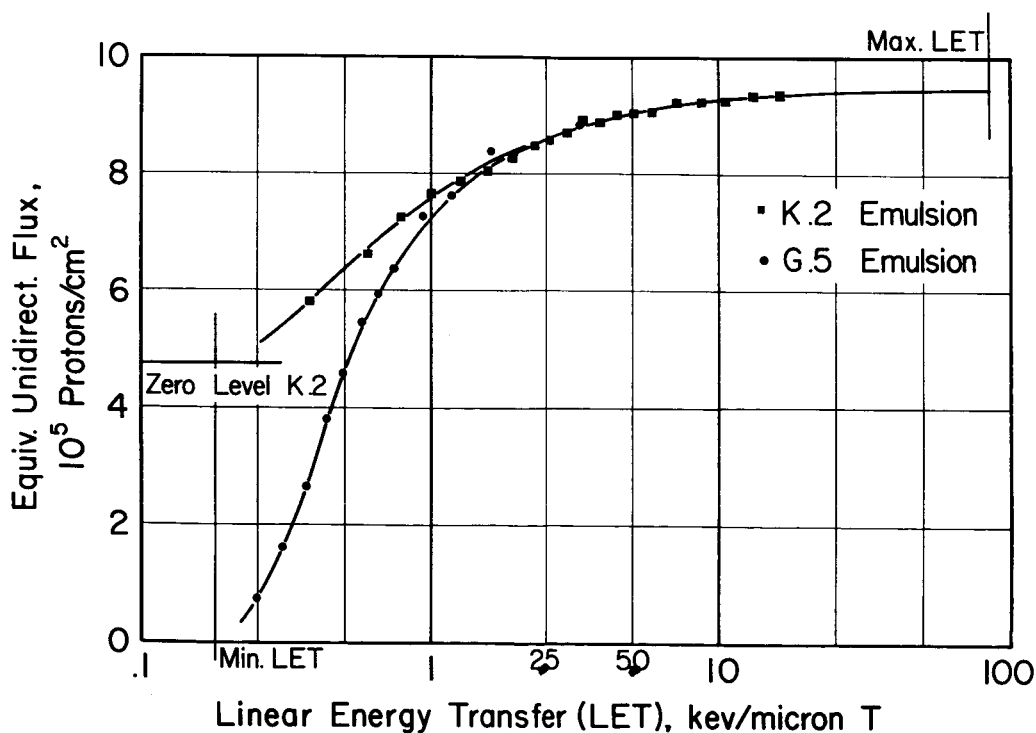


Figure 1

Integral LET Spectra Obtained from Track and Grain Count of K.2/G.5 Emulsion Pair (Command Pilot, Thigh) on Gemini VII

Ordinate values show integral flux from LET_{min} to LET.

Figure 1 presents the integral LET spectra of the track populations in the G.5 and K.2 emulsion sheets from the pack at the indicated location. The squares and dots directly show scanning scores expressed in terms of equivalent unidirectional flux as explained in an earlier report (3); the squares indicate K.2 scores and the dots, G.5 scores. Since the K.2 emulsion has limited resolution in the sense that, depending on background, proton tracks for energies beyond 50 to 80 Mev can no longer be recognized, the grand total of all identified tracks in a K.2 scan is substantially smaller than in a G.5 scan for the same exposure. For the data presented in Figure 1 the pertinent flux values are 945,000 protons/cm² for the G.5 emulsion and 470,000 protons/cm² for the K.2. By adding the difference of 475,000 protons/cm² as a constant value to all scores of the K.2 scan, the entire K.2 spectrum can be lifted on the ordinate scale by such an amount that the upper ends of the G.5 and K.2 spectra coincide. This adjustment of the K.2 spectrum has been carried out in Figure 1. It demonstrates well the fact that in the region of high LET values, from about 2 kev/micron T on, both emulsions have the same sensitivity. As LET decreases, more and more tracks are missed in the K.2 scan, as indicated by the smaller slope of the integral spectrum. Figure 1 also identifies well the respective regions of maximum accuracy for the K.2 (squares) and G.5 (dots) emulsion. The smooth curves drawn in Figure 1 are intuitive estimates of best fit. The large sigmoid curve running smoothly through all points covering the scans from both emulsion types has been used for further evaluation.

Figure 2 presents the differential LET spectrum as it follows from the just-mentioned compound integral spectrum of Figure 1. The ordinate shows differential flux for a constant abscissa interval of $\Delta \log \text{LET} = 0.1$, i.e., for 1/10 of one decadic unit of the abscissa scale. In a dosimetric interpretation of Figure 2 one should realize that, in order to obtain the differential dose contribution, the differential flux has to be multiplied by the LET. The maximum of the differential flux at about 0.5 kev/micron T, therefore, does not necessarily mean that protons in this particular LET interval furnish the largest contribution to the total dose. That there is indeed no particular region of the logarithmic LET scale in which the energy dissipation is concentrated can be seen from the curve of the cumulative dose which also is drawn in Figure 2. It was obtained by breaking down the total LET interval from 0.18 to 85 kev/micron T into small intervals and determining the dose increment for each interval. The cumulative dose is plotted in percentage of the total dose of 190 millirads so that it shows directly the relative share for any LET value.

If the slight waviness of the main part of the curve showing cumulative dose is disregarded, the differential dose contribution in a logarithmic LET plot is found to be constant, as indicated by the constant slope. Merely in close vicinity of the maximum (Bragg peaks of terminating protons) and minimum LET (relativistic protons) does the differential dose seem to be smaller. For the Bragg peaks from "enders," this statement is actually not meaningful because the precipitous increase and decrease of the LET in the Bragg peak in connection with the straggling phenomenon produces a quasi-discontinuity in the curve of the cumulative dose. These relationships have been discussed in an earlier report when similar measurements on Project Mercury were presented (3).

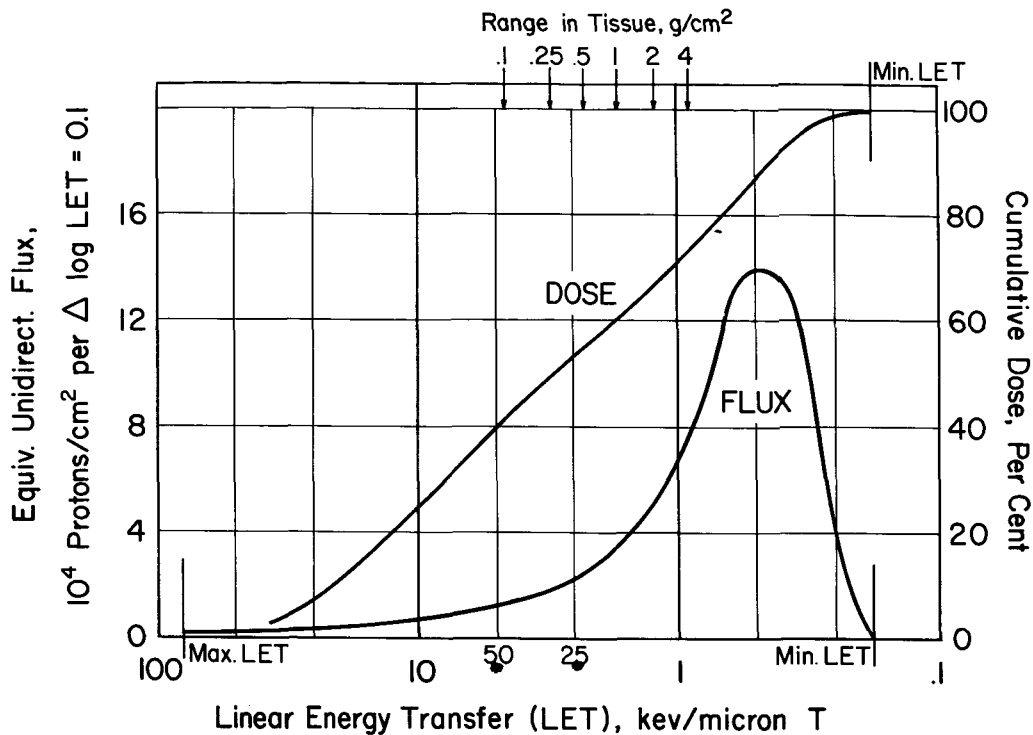


Figure 2

Differential LET Spectrum and Cumulative Dose for Radiation Pack No. 4

Data are based on smooth curve of integral LET spectrum for G.5 emulsion in Figure 1. Note reversed abscissa scale.

In order to facilitate interpretation of the data in Figure 2 in terms of penetrating power, selected range values in tissue are marked on the upper abscissa scale. It is seen that about 40 per cent of the total dose is produced by protons of less than 0.1 g/cm² penetrating power and 60 per cent by protons of less than 1.0 g/cm². This finding suggests that local shielding conditions should influence strongly the local flux and the local dose. How far this can be verified from the emulsion recordings will be discussed in the next section.

ANALYSIS OF ENDERS

The shield distribution about the individual radiation pack reflects the complex structural geometry of vehicle frame, equipment, and the astronauts' bodies. Although the shield distribution of the Gemini vehicle has been analyzed (4), no attempt was made on the Gemini missions to actually trace the differences between readings of different radiation packs to this distribution. This would have required additional provisions for recording attitude and position of the packs during passes through the Anomaly, which was not feasible because the radiation monitoring was to be accomplished with as little

interference to the astronauts as possible. It seems nevertheless of interest to investigate whether and to what extent anisotropies in the track populations of the film sheets do exist even though they cannot be traced to patterns in the shield distribution.

For obvious reasons, one would expect the most pronounced variations of local flux for protons of lowest energies; hence, the best experimental approach would seem to determine the "enders" count, i.e., the number of proton tracks ending in the emulsion. This would be of interest not only for different packs but even for different local areas on the same emulsion sheet. For reasons of time economy, it was not possible to subject the same film sheet to a grain count analysis for establishing the LET spectrum and to a complete enders tally. Since the two evaluation procedures differ basically, they cannot be carried out simultaneously in the same scan. Therefore, the emulsion pair of Pack No. 4, for which the complete LET spectrum has been established as described in the preceding section, was subjected only to a plain enders count for the local area on the film sheet where the grain count analysis had been carried out. This enders count was found to be 32.2 enders per mm^2 emulsion area. This is the net value corrected for enders from disintegration stars (20 per cent) and for enders in the sea level controls (about 4 per cent).

A thorough scan of the local variation of the enders count on the same film sheet has been carried out for the 200 micra K.2 pellicle in Pack No. 9 (pilot, thigh pocket). Figure 3 and Table I show the results of this scan. Emulsion areas of 5 to 12 mm^2 have

Table I
Local Frequencies of Proton Enders in K.2 Emulsion of Radiation
Pack 9 on Gemini VII

Location (See Figure 3)	Enders per mm^2	Total Number of Enders Counted
I	29.9	363
II	34.7	91
III	34.4	201
IV	34.2	234
V	34.7	454
VI	35.8	199
VII	38.4	238
VIII	39.8	170
IX	40.2	228
Mean	34.8	Sum 2178

been enders counted at locations marked by circled x-marks in Figure 3. The isofrequency contours drawn in Figure 3 are estimates which are intended merely to demonstrate that the intensity gradient does not exhibit a simple uniform pattern. It is obvious that spot checks at only nine locations are quite insufficient for determining the details of such a complex pattern as seems to exist in the emulsions of Pack No. 9. However, since a more specific interpretation of the variations of the enders count in terms of the shield distribution about the radiation pack is not possible for reasons explained before, a complete enders count of the full emulsion area was set aside.

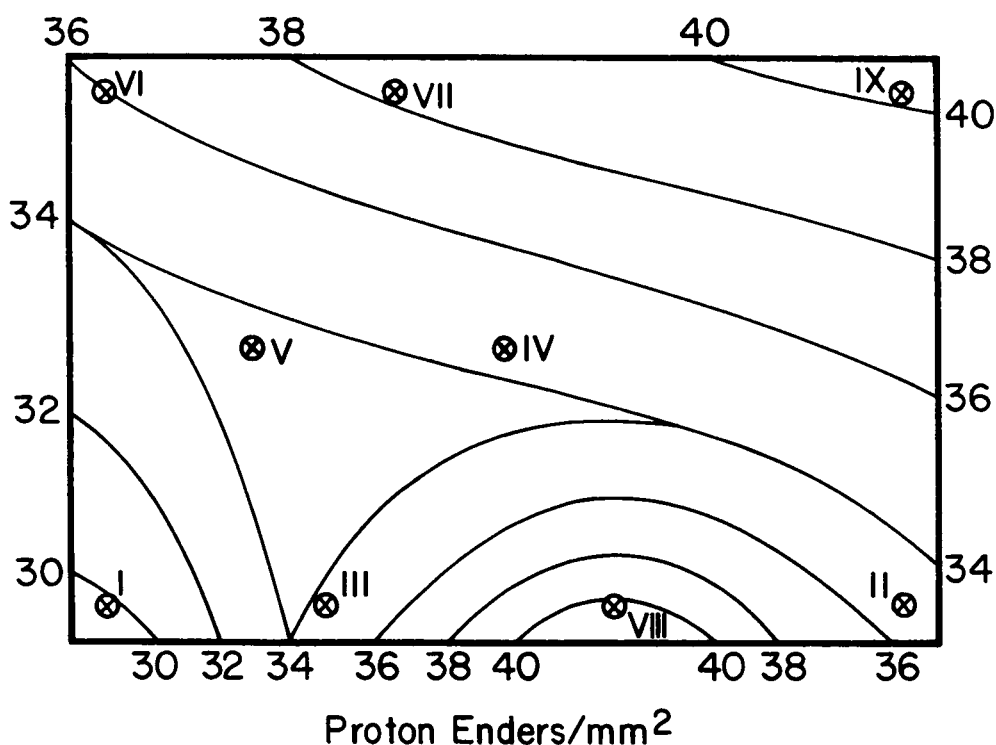


Figure 3

Estimated Isofrequency Patterns of Proton Enders in K.2 Emulsion of Radiation Pack No. 9 (Pilot, Thigh)

Circled x-marks show locations where enders counts were taken. Counts are listed in Table I. Size of emulsion sheet: $1 \times 1\frac{1}{2}$ inches.

The pronounced variations of the local enders count shown in Figure 3 raise the question whether similar anisotropies exist in the directional distribution in the sense that preferred and depleted directions of incidence can be identified for protons ending in the emulsion. For reasons of time economy, recording the direction of incidence has

been limited in all enders scans so far to the plane of the emulsion. Determination of the dip angle at which a proton has entered the unprocessed emulsion is an involved procedure because of the shrinkage of the emulsion in processing which produces a non-linear distortion of the original distribution of dip angles.

The polar diagram in Figure 4 shows the directional distribution for the grand total of all enders of Figure 3 in the two-dimensional plane parallel to the emulsion. The diagram indicates a pronounced and complex anisotropy, with a sharper maximum at the SSE, and a broader maximum at the NNE, and a broad pronounced minimum at the WSW. It would be of even greater interest to establish similar directional diagrams for the individual locations on the film sheet where enders counts were taken as indicated in

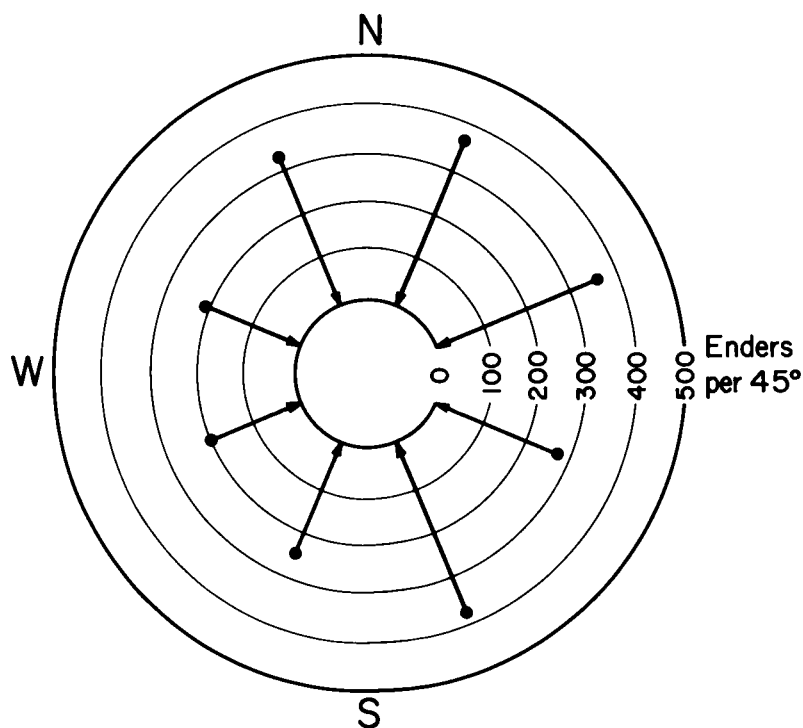


Figure 4

Directional Incidence of Protons Ending in the Emulsion in Radiation
Pack No. 9

Shown is projection of true incidence on the emulsion plane.
Compass directions refer to film sheet. Absolute orientation
is unknown.

Figure 3. Unfortunately, this creates the problem of an insufficient statistical significance because in the process of breaking down the already small enders population at one location into eight fractions corresponding to eight directions, the enders frequency for the individual direction becomes too small. If an attempt is made to overcome this difficulty by scanning a larger area at a given location on the film sheet, the true changes of the local enders count would make themselves felt and blend in an uncontrollable way with the statistical variations. At the exposure level encountered on Gemini VII, one has only the two alternatives of determining either the changes of the local frequency of enders in the film sheet without resolving direction of incidence or the directional anisotropy without resolving local changes.

Since scanning the track population in a given emulsion area for enders requires considerably less time than a grain count analysis of all tracks, it is of some interest to examine to what degree the enders count alone could be relied upon for dose estimates. In Report 33 the transition of the energy spectrum as recorded on Gemini IV was analyzed for progressive attenuation in nuclear emulsion under the assumption of unidirectional incidence. Though the enders count is not expressly mentioned in Report 33, the pertinent data show that, for the same increment in absorber thickness, the enders count drops somewhat more rapidly than the total dose. Nevertheless, it can be used for an approximate determination of dose as long as the spectral configuration of the incident radiation remains the same and variations in the shield distribution are moderate. With this assumption, the enders counts found in the radiation packs of Gemini VII can be used for estimating the corresponding doses using the ratio of 190 millirads per 32.2 enders/mm² as found in Pack 4. Table II shows the pertinent data. It should be mentioned that the data reflect the scanning scores available at the time this report is being

Table II

Enders Counts and Doses Recorded in Radiation Packs on Gemini VII

Pack No.	Location	Enders/mm ²	Total Proton Dose, mrad
Command Pilot:			
2	Right Chest	30	177
3	Left Chest	37	218
4	Thigh	32.2	190
Pilot:			
7	Right Chest	39.5	233
8	Left Chest	27	159
9	Thigh	34.8	205

written. They do not come anywhere near to a complete account of the information contained in the emulsions. The only exceptions to this restriction are the enders counts of Packs 4, 7, and 9 which can be considered representative mean values for the entire film area. In any case, even these preliminary data demonstrate the great variations of the local radiation level within the vehicle.

CONCLUSIONS

The findings reported in the present study for Gemini VII agree well with those reported earlier for the missions Gemini IV and V in Report 33. In fact, a detailed comparison of the track and grain count scores indicates for Gemini VII a slightly larger relative share of low energy particles in the total flux. Whether this is a general characteristic for all packs of Gemini VII cannot be decided yet because so far a statistically satisfactory evaluation of the LET spectrum is available only for one partial area of the films in Pack 4.

It is felt that the statement made in Report 33 concerning the dose contribution from electrons and gamma rays is well borne out by a visual comparison of the background of flown and control G.5 emulsions of Gemini VII in the sense that the dose contribution in question is substantially smaller than the proton dose. Figure 5 shows a micrograph of the G.5 emulsion in Pack 2 (command pilot, right chest).

With regard to heavy nuclei, it should be pointed out that those heavy tracks which still can be grain counted are treated as protons in the scan. That means their dose contribution is correctly assessed. It would in fact be more correct to replace, throughout this report, the term "proton dose" by "dose from all grain-countable tracks." A scan for heavy tracks with solid silver cores that cannot be grain counted is under way yet still incomplete and shall be reported on at a later time. Figure 6 shows a heavy track of an estimated $Z = 10$ in the G.5 emulsion of Pack 2. The data accumulated so far are in good agreement with the findings reported in Report 33, pointing to a dose contribution from heavy nuclei of about 5 per cent of the total dose in rad. It is, of course, an entirely different question as to how much this particular fraction of the total energy dissipation in tissue would weigh, if one proceeds from absorbed doses in millirads to dose equivalents in millirems for assessing the true radiation load, especially from repeated or long-term exposures. However, the radiation safety aspects of the reported findings shall not be discussed here.

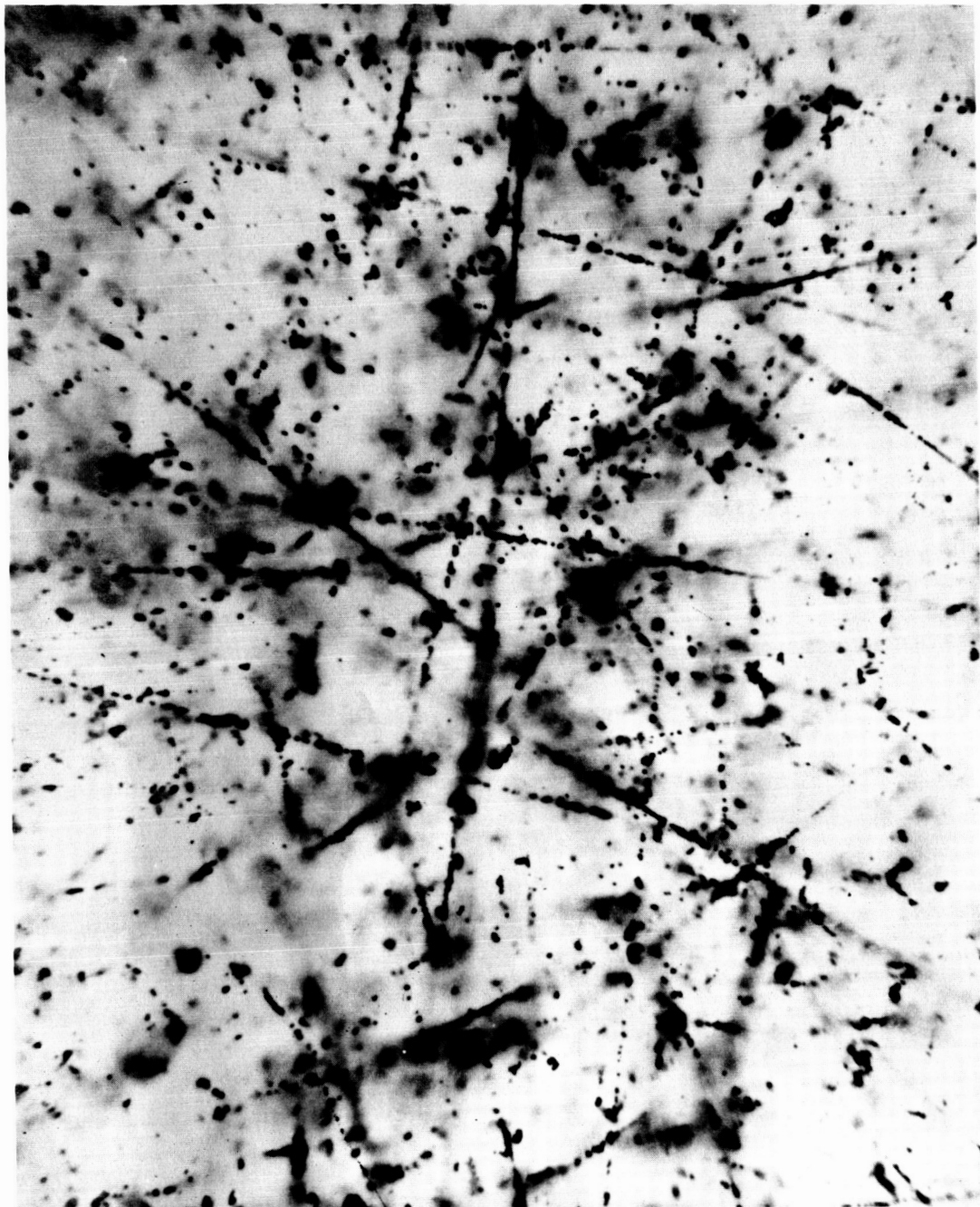


Figure 5

Micrograph of Typical Visual Field Taken from G.5 Emulsion of Radiation
Pack No. 2 (Command Pilot, Right Chest)

Field Size: 199 x 248 micra.

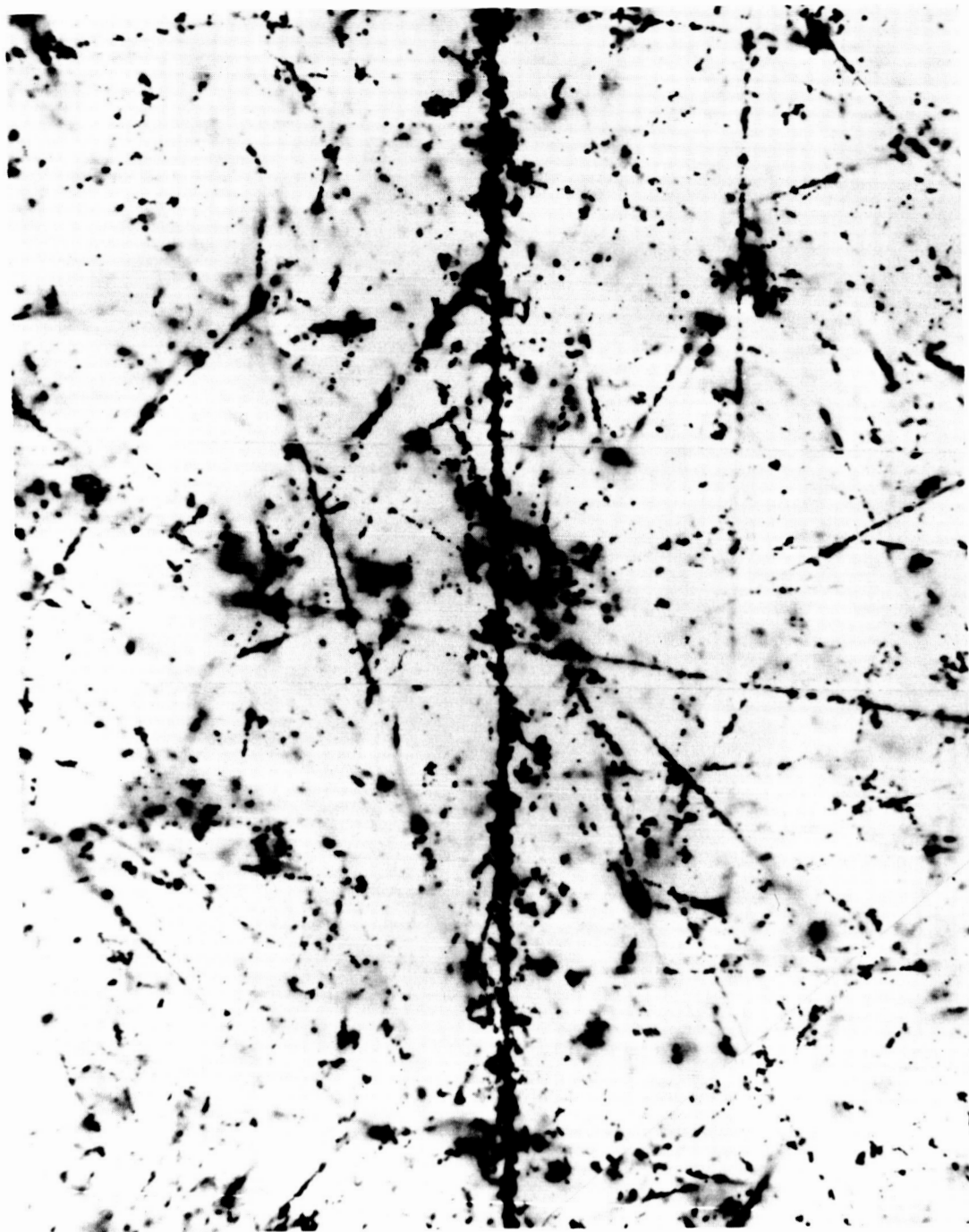


Figure 6

Micrograph of Atypical Visual Field of Same Emulsion Sheet as Figure 5,
Showing Track of Heavy Nucleus of Estimated $Z = 10$

Field Size: 198×256 micra.

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<p>Small nuclear emulsion packs worn by the astronauts at three locations inside their space suits were evaluated by track, grain, and enders count for evaluation of LET spectrum and absorbed dose. By using G.5/K.2 emulsion pairs, a sustained resolution over the entire LET scale of protons from zero to relativistic energies was obtained. It was found that the energy dissipation centers heavily on low energies, with 40 per cent of the absorbed dose due to protons of less than 0.1 g/cm² residual range. Total proton doses at the six locations (left and right chest, thigh pocket of each astronaut) varied from 159 to 233 millirads. The enders count was found to vary by as much as a factor of 1.35 within the same 1 by 1½-inch film sheet, indicating that the radiation field within the vehicle not only varies over distances comparable to body size, but also reflects local inhomogeneities of shielding conditions on a centimeter and millimeter scale.</p>		

14. KEY WORDS	LINK A		LINK B		LINK C	
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Radiation hazards in space Radiation exposure of astronauts on Gemini VII LET spectrum of trapped protons inside Gemini vehicle Nuclear emulsion measurements of protons in South Atlantic Anomaly						

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